Impact of Chromatic Effects on Measurements of Galaxy Position, Shape and Flux

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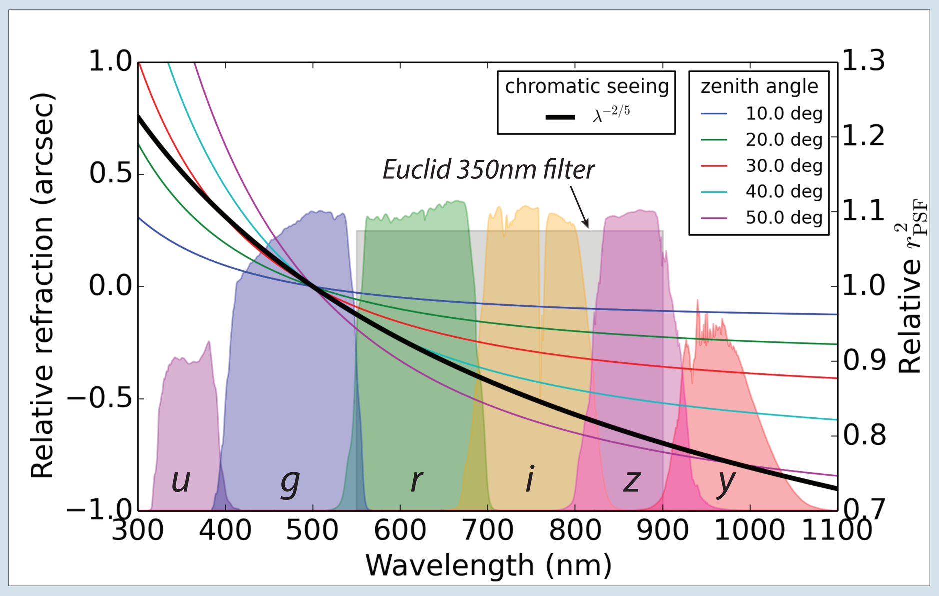
Introduction

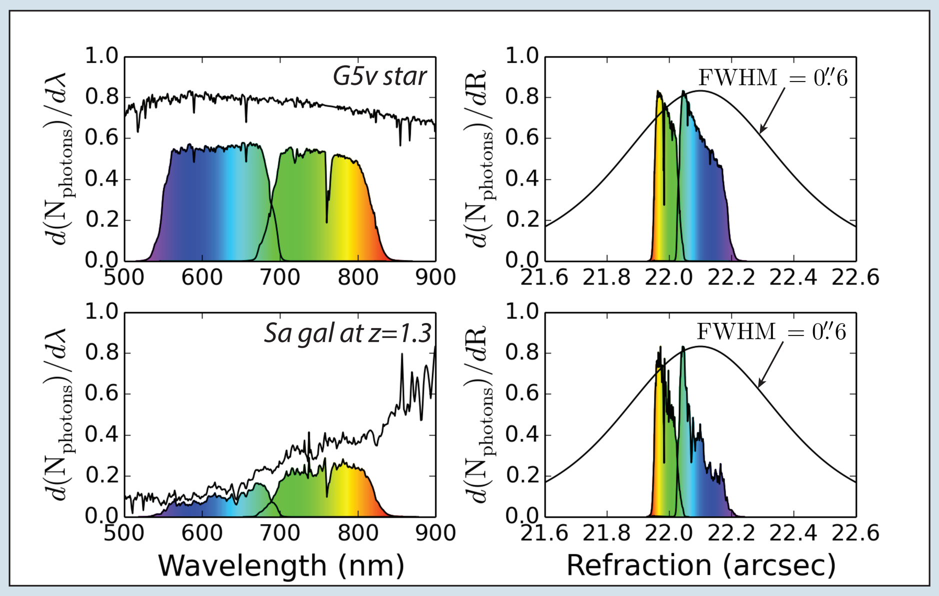
- Precision measurements of fluxes, positions, and shapes of galaxies typically depend on measurements made with stars since galaxy images are deconvolved with stellar point spread functions (PSF).
- Approach assumes stellar PSF is same as PSF for galaxies.
- If PSF is dependent on wavelength, assumption is violated since stars and galaxies have different spectral energy distributions (SEDs).



Top: Two chromatic PSF effects originating in the atmosphere.

1) Differential chromatic refraction (DCR) - All photons entering the atmosphere from space are refracted towards the zenith, but bluer photons are refracted slightly more. This leads to SED-dependent stretching and contracting of the PSF in the zenith direction.

2) Wavelength dependence of seeing - Fluctuations in the refractive index of turbulent cells in the atmosphere lead to seeing that is dependent on wavelength.



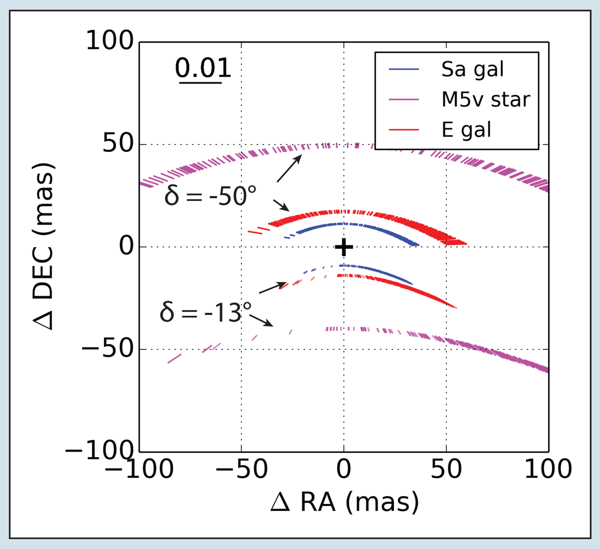
Bottom: Impact of SED and differential chromatic refraction on PSF.

Left - Detected photons binned by wavelength in LSST r- and i-band filters for two different spectra.

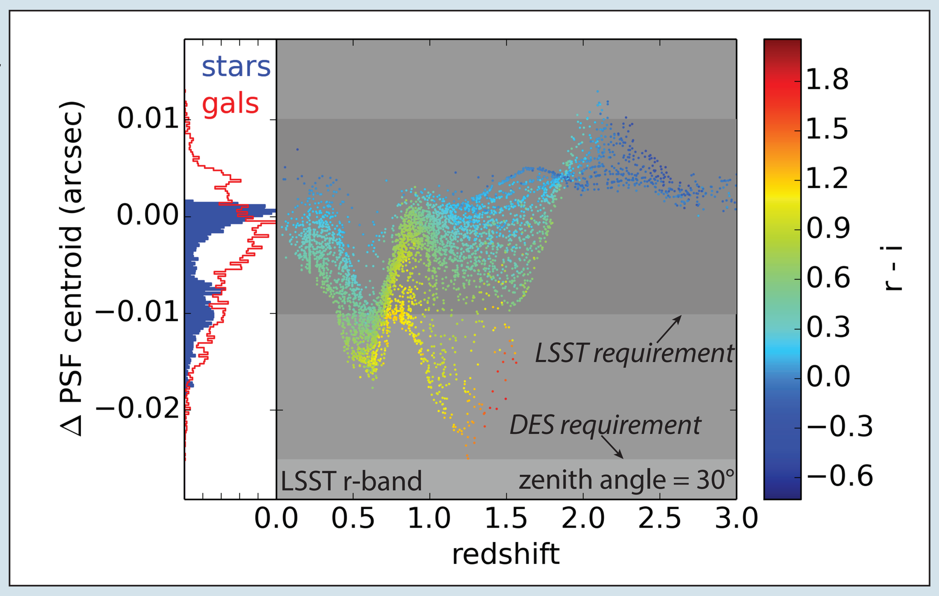
Right - Same photons binned by refraction angle. Difference in distributions of refraction angle leads to differences in PSF zenith-direction centroids and second moments.

Centroid Shifts Due to Differential Chromatic Refraction

SED-dependent centroid shifts complicate process of registering multiple exposures of same patch of sky taken at different hour angles, since both magnitude and direction of centroid shifts will vary.



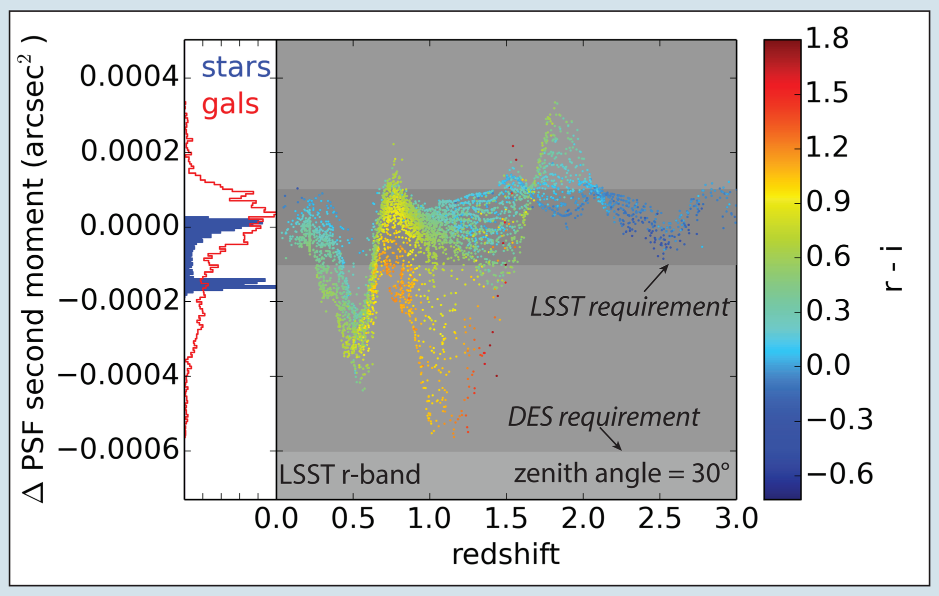
Top: Centroid shifts for objects with three different SEDs, relative to a G5v star, as observed in LSST survey, for two different declination angles. (Visit parameters obtained from LSST Operations Simulator run 3.61.) Length and direction of plotting symbols indicate difference in PSF ellipticity relative to the G5v star (see next panel). Note that the figure area subtends one LSST pixel.



Bottom: Centroid shifts relative to G5v star for LSST at zenith angle of 30°, where LSST will often observe. SEDs are drawn from LSST ImSim catalog with i-band magnitude limit of 25.3, corresponding to "LSST gold sample" for weak lensing. Note that centroids of stars and galaxies vary, and the centroid shifts of galaxies are correlated with redshift, potentially introducing redshift-dependent calibration biases. Plazas and Bernstein (2012) estimate that RMS centroid shifts of 0.01 (0.025) arcseconds will produce systematic uncertainties in dark energy parameters of order the statistical uncertainties for LSST (DES).

Ellipticity Shifts Due to Differential Chromatic Refraction

Stretching and compressing of PSF along zenith direction due to DCR also leads to SED-dependence of PSF ellipticity, as blue photons land slightly closer to zenith than red photons.



Top: Zenith-direction second moment shifts relative to G5v star at zenith angle of 30°, as observed by LSST. Plazas and Bernstein (2012) estimate that second moments shifts of galaxies need to match second moment shifts of PSF stars to 0.0001 (0.0006) arcsec² for LSST (DES) in order for systematic uncertainties on dark energy parameters to not dominate statistical uncertainties.

Bottom: Estimating ellipticity of galaxy by fitting parameterized model to image leads to additional biases when PSF is misestimated.

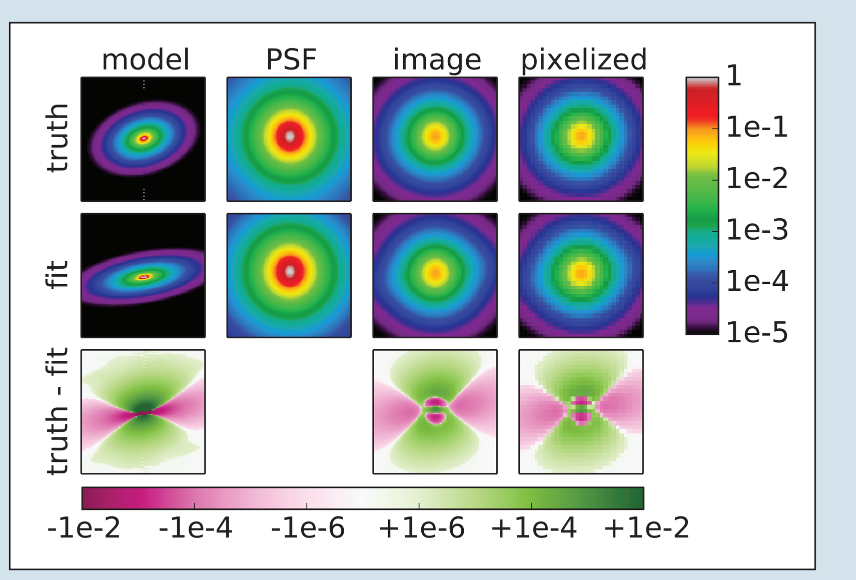
Upper row - True galaxy model is convolved with galactic PSF and then pixelized.

Middle row - Model parameters are varied until convolution with incorrect (stellar) PSF minimizes residuals of pixelized image.

Bottom row - Residuals.

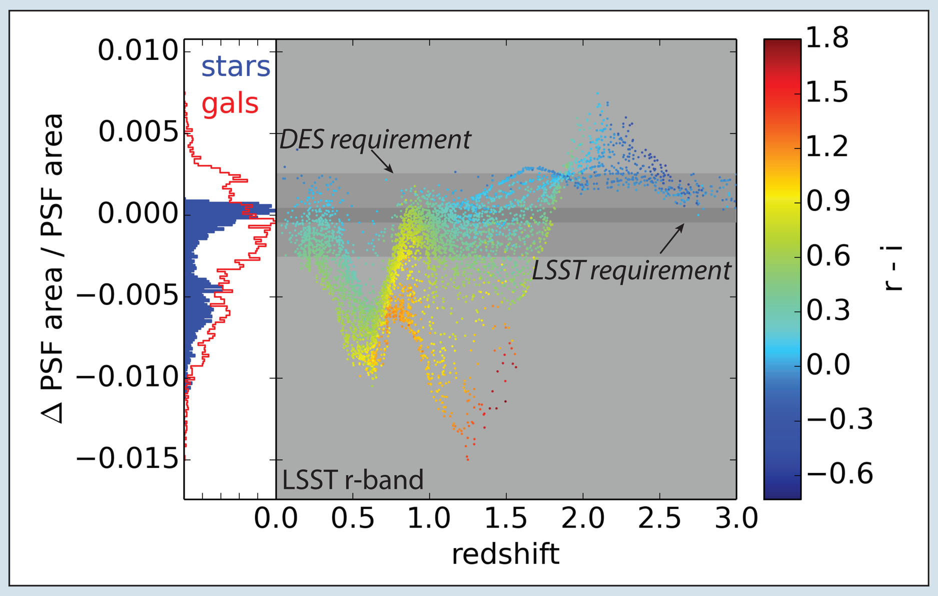
In this contrived example, the stellar PSF is elongated in the vertical direction relative to the galactic PSF, which manifests in a best fit model that is too narrow.

Additional uncertainty arises because no model parameters exist to exactly reproduce the true pixelized image when convolved with the stellar PSF (see finite pixelized image residuals).

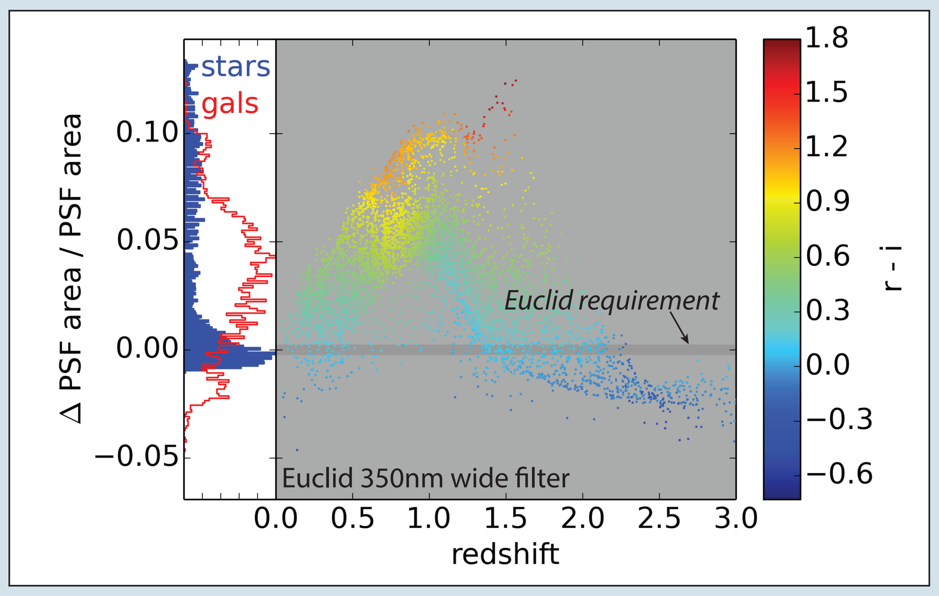


Size Shifts

- PSFs for large ground-based telescopes are dominated by atmospheric seeing.
- Blue photons are smeared out by the atmosphere more than red photons; PSF scales with wavelength like $\mathrm{FWHM} \propto \lambda^{-1/5}$
- Chromaticity of space-based telescope PSFs are dominated by diffraction limit of primary aperture; PSF scales like $\mathrm{FWHM} \propto \lambda^{+1}$ (after adding contribution from CCDs and jitter, scaling is more like $\mathrm{FWHM} \propto \lambda^{+0.6}$ (Voigt et al. 2012))
- Incorrect PSF size estimate propagates to incorrect estimate of galaxy "roundness".
- Survey requirements for PSF size depend on power law index of size-wavelength relation, filter bandwidth, and relative size of PSF to size of galaxies.



Top: PSF size (area), relative to G5v star, for LSST r-band due to chromatic seeing. Fractional area of galaxy deconvolution kernel needs to be known to 4×10^{-4} (25×10^{-4}) in order for LSST (DES) systematic uncertainties on dark energy to not dominate statistical uncertainties.



Middle: PSF size (area), relative to G5v star, for Euclid-like 350nm-wide optical band, assuming PSF width dependence $\mathrm{FWHM} \propto \lambda^{+0.6}$. Fractional area of Euclid PSF needs to be known to 2×10^{-3} to limit dark energy systematics.

Note that ratio of PSF size variability to PSF size requirements are similar for Euclid and LSST: LSST has smaller wavelength dependence, but a larger PSF.

Bottom: Estimating ellipticity of galaxy by fitting parameterized model to image leads to additional biases when PSF size is misestimated.

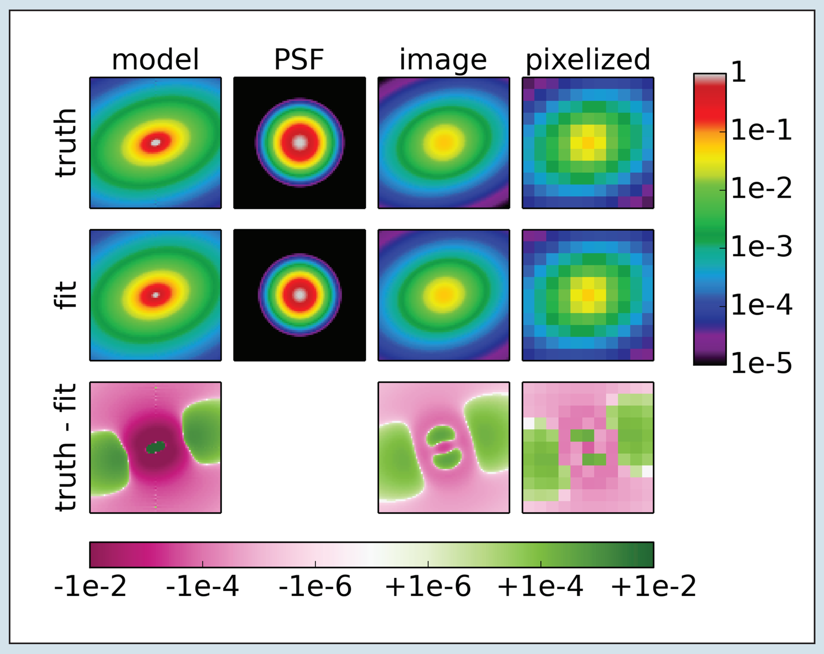
Upper row - True galaxy model is convolved with galactic PSF and then pixelized.

Middle row - Model parameters are varied until convolution with incorrect (stellar) PSF minimizes residuals of pixelized image.

Bottom row - Residuals.

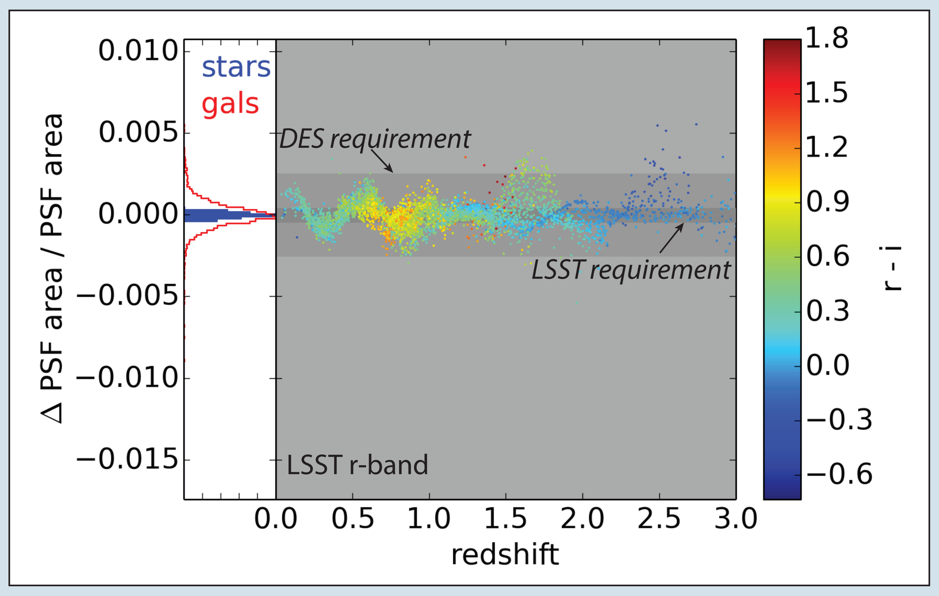
In this contrived example, the stellar PSF is isotropically smaller than the galactic PSF, which manifests in a best fit model that is too round.

Additional uncertainty arises because no model parameters exist to exactly reproduce the true pixelized image when convolved with the stellar PSF (see finite pixelized image residuals).

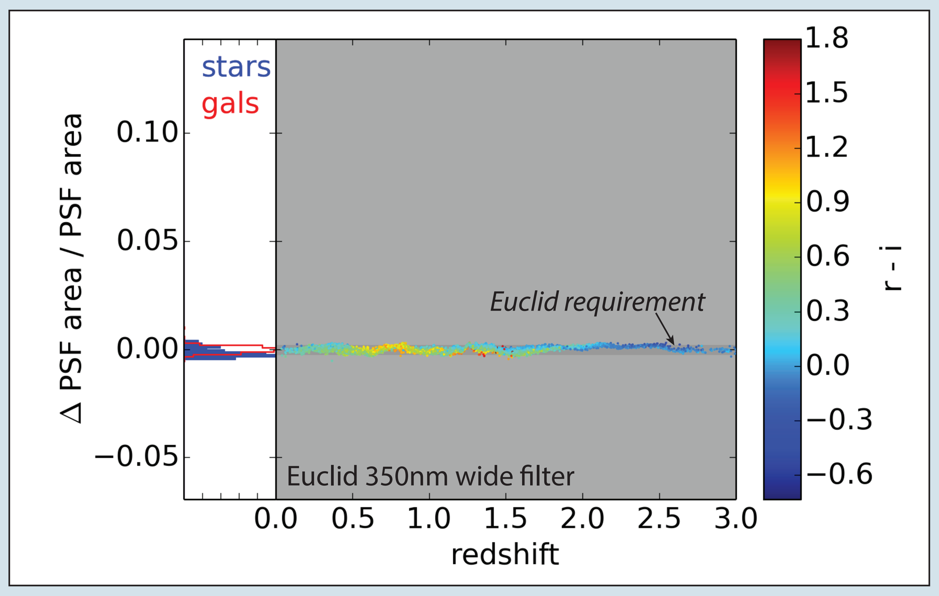


Machine Learning to Correct PSF Biases

Chromatic PSF biases can be corrected provided that SEDs of stars and galaxies are known. Since SEDs are partially encoded in photometry of surveys, machine learning algorithms can be trained to predict PSF corrections from photometry.



Top: Residual bias after applying Support Vector Regression algorithm to learn LSST PSF size as function of LSST photometry. The size-photometry relation for stellar PSFs is easily learned by the algorithm. However, the relation for galaxies is more difficult due to their much larger spectral variation. Note the mean bias depends on redshift, which leads directly to redshift dependent bias on cosmic shear.



Bottom: Residual bias after applying Support Vector Regression algorithm to learn Euclid PSF size from LSST photometry. Since Euclid 350nm optical filter spans LSST r-, i-, and z-bands, the SED is well constrained. Support Vector Regression easily learns the relation between photometry and PSF size. Note that the LSST sky overlaps the proposed Euclid sky by 5000 square degrees.

Ongoing and future work

Outstanding questions:

- What biases are introduced by chromatic effects in the optics and the CCD response? (Or by similar non-chromatic effects, such as PSF size vs. magnitude?)
- How do these biases vary across the focal plane?

Ongoing work:

- How well can chromatic biases in measurements of astrometry, shape and photometry be corrected (e.g., with machine learning based on multi-filter photometry)?
- How do residual chromatic biases affect estimators of cosmic shear and photometric redshifts?
- What is the impact of residual biases on measurements of cosmological parameters when biases may depend on object's position on the sky or on the focal plane?